Design and demonstration of a wireless sensor network platform for substation asset management

Citation for published version:
Huynh, N, Robu, V, Flynn, D, Rowland, S & Coapes, G 2017, 'Design and demonstration of a wireless sensor network platform for substation asset management', *CIRED - Open Access Proceedings Journal* , vol. 2017, no. 1, pp. 105-108. https://doi.org/10.1049/oap-cired.2017.0273

Digital Object Identifier (DOI):
10.1049/oap-cired.2017.0273

Link:
Link to publication record in Heriot-Watt Research Portal

Document Version:
Publisher's PDF, also known as Version of record

Published In:
CIRED - Open Access Proceedings Journal

24th International Conference & Exhibition on Electricity Distribution (CIRED)
12-15 June 2017
Session 1: Network components

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Journals
The Institution of Engineering and Technology
ISSN 2515-0855
doi: 10.1049/oap-cired.2017.0273
www.ietdl.org

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Abstract: A key challenge for distribution and transmission system operators is to relate the retrofitting of monitoring systems to support asset management aligned with the continuity of service within the electrical network. The research within this study demonstrates how a Smart System Integration approach, utilising a wireless sensor network (WSN), can provide a low cost and scalable sensor platform for in situ sensing of SF6 within substations. In this study, the design and manufacturing stages of an ultra-low power WSN are outlined. The WSN is evaluated within a high-voltage laboratory and deployed within a 400 kV substation. Results indicated that the system can reliably transmit data within a noise environment, recover when there is a mote failure without data loss, can operate on batteries for 1.5 years or 5 years taking 1 SF6 density measurement every 60 or 300 s, respectively. The findings of this research demonstrated the advantageous features of WSNs, namely low cost, rapid deployment, reliable and secure data transfer, adaptive and scalable sensor platform.

1 Introduction

There is currently no economy in the world that can replace its transmission and distribution network. To provide a context, it is estimated that the grid within the United States requires around $2 trillion in upgrades by 2030 [1]. In the UK, the Department of Energy and Climate Change (DECC) estimated that between 2010 and 2014 there would have been over £16 billion of investment in the electricity network. Further to that, they estimate that between 2014 and 2020 a further £34 billion needs to be invested [2]. Unsurprisingly, there is a global preference to defer investment in the existing electrical networks, creating a demand for the services of asset management solution providers that can provide visibility to distribution system operators (DSOs)/transmission system operators (TSOs) to the current health of the asset base throughout the network and support asset life extension of critical assets. In delivering such technical solutions, companies have to contend with an aging asset base, increasing consumer demand for electricity and the integration of new technologies, e.g. renewable energy technologies, into the network. Over the last 15 years there have been serious disruptions to the power grid in Europe, Asia and America, which have exemplified the risks and effective asset management solutions have not been present [3–6], which have had serious economic impacts.

One of the most severe blackouts to have occurred in the last 20 years was the 2003 Northwest US-Canada blackout [3]. Due to the lack of system visibility and a very serious IT system failure, the system operators lost situational awareness of the power grid in their care. An unfortunate combination of a grid with limited monitoring, IT failure and an unforeseen power plant failure meant that the Northeast power system collapsed. This resulted in economic damage estimated at between $4.5 and $10 billion across manufacturing, service and government industries [4]. It is becoming more and more important to industrial power customers to ensure good power quality and reliability, such as for centralised data servers [5]. These are critical elements of Internet infrastructure that are absolutely dependent on the electricity network to maintain their operation.

In July 2012, India suffered the world's most widespread electricity grid failure, which at its worst extent had isolated almost the entire Northern, Eastern and North-Eastern Electricity grid. The Ministry of Power report of August 2012 [6] identified several key factors in this failure. The first was that the Indian power operators had scheduled, in error, a series of major outages and had severely weakened key inter-regional power interconnections. This led to severe overloading and tripped the line. However, neither on 30 nor 31 July was a fault actually observed in the system, indicating a clear lack of system visibility. The lack of available telemetry data crippled the observability and state estimation of the Indian grid and prevented the load dispatch centres from shedding load effectively.

It is clear that for the globe to have a resilient and sustainable electricity network, enabling technologies, commonly referred to as Internet of things (IoT), wireless sensor networks (WSNs) and cloud computing platforms, have to be deployed and integrated into operational decision support systems that support health management of the electrical network. Albeit that IoT terminology refers to 'things' and WSNs are commonly referred to as being attached to 'assets' the reality is that this technical evolution in monitoring systems is actually about a *technology as a service* trend. This trend is driving a transition from product centric to service centric business models where the emphasis is on the continuity and improvement of service(s). The levelised cost of electricity (LCOE) is more likely to remain accessible to all, even with the adoption of more expensive generation technologies, through commercial and technical management that places an emphasis on lifecycle costs through a system engineering-based approach.

Within this work, we demonstrate how commercial off-the-shelf (COTS) technology can be designed into a WSN for gas-insulated substation (GIS) condition monitoring. Sulphur hexafluoride (SF6), thanks to its excellent dielectric properties, has been extensively used not only as insulation but as arc-quenching medium in GIS since 1960. The majority of the equipment within a GIS e.g. switchgears, bus-bars, transformers etc. are housed in metal enclosed modules filled with SF6. SF6 usage within the electrical network represents 80% of worldwide consumption and the sector equates to 0.1% of greenhouse gas emissions. The challenge this represents is likely to increase as the global cumulative number of transmission substations is expected to increase to 219,905 units by 2020 based on a compound annual growth rate (CAGR) of 5.2% [7]. In light of this, as of 1 January 2017, the UK government requires that you must fit monitoring equipment on any new asset that contains more than 22 kg of SF6.

Conventional substation monitoring e.g. gas density monitoring (GDM) requires significant financial investment to support the installation, inspection and periodic maintenance of cables and monitoring devices. In this work, we will explore the alternative of a WSN for GDM and demonstrate the potential of smart system integration of COTS technology for the electricity network.

2 Specification of the WSN

The transition from traditional GDM system to WSN-enabled GDM system is illustrated in Fig 1. The specification of this demonstrator is summarised in Table 1.

A review of WSN manufacturers identified the Linear Technology's Dust Networks, SmartMesh IP, as the leading technology for this application [7]. SmartMesh IP promotes IPv6-ready, ultra-low power or even battery-free solutions for wireless monitoring and diagnostics specifically in harsh and high radio frequency (RF) interference environments. The SmartMesh network is a self-forming, self-healing, full mesh, consisting of at least one SmartMesh manager and maximum 100 SmartMesh IP motes or 500 SmartMesh WirelessHART motes for each manager. Unlike alternative technologies such as ZigBee, every mote in SmartMesh network possesses the full functions of a router, enabling any new mote to join the network through its nearby motes as well as offering multiple data routing paths for flexibly data transmission.

The key technology behind the advancement of SmartMesh network is the proprietary time synchronised mesh protocol (TSMP) introduced and developed by Dust Networks which divides up network time into timeslots, resulting in collision-free packet exchange, per-transmission channel-hopping and ultra-low power communication [7].

In the wireless sensor units, motes, the SF6 gas density is measured by using a digital gas sensor, Trafag 8775. The sensor is a recently introduced product by Swiss-based Trafag AG specifically designed for the monitoring of insulation gases [8]. The sensor includes a built-in temperature sensor. Based on the gas density and temperature measurements, the sensor delivers gas pressure at measured temperature, also known as non-compensated pressure. To enable the Trafag to communicate with the SmartMesh IP a sensor driver circuit is developed featuring serial peripheral interface (SPI) to Modbus RS-485 conversion. This is shown in Fig. 2, along with the sensor duty-cycling circuit. Duty cycling the sensor is expected to conserve a considerable amount of energy, enabling to further extend the battery life by keeping the sensor operational only for the time needed for obtaining a new set of samples and holding it off or in low-power mode right after completion of acquisition.

When identifying a battery to match the performance requirements of the WSN five major metrics are used: rated/nominal voltage, maximum current, capacity, discharge characteristic and temperature effect on capacity. Due to the high-energy density, high capacity and small self-discharge rate, lithium batteries are the ideal candidate for long-term applications which require very low current draw. The details of the battery solution from Cell Pack solutions is summarised in Table 2.

The following section provides an overview of the WSN mote assemblies.

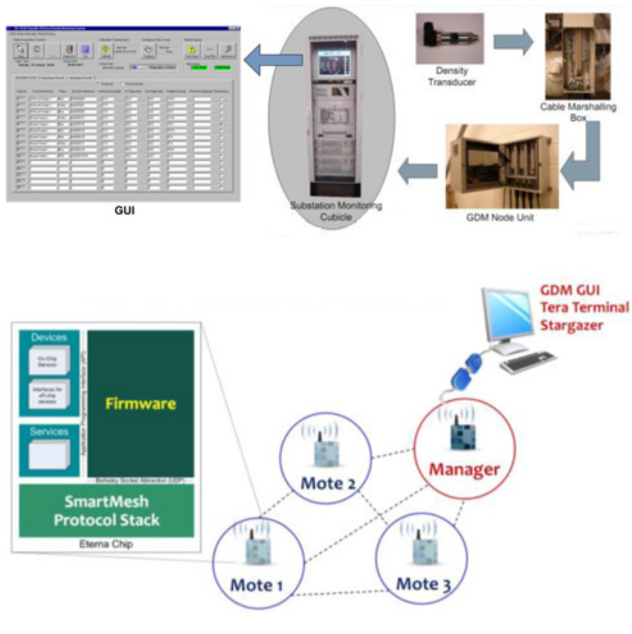

Fig. 1 *Traditional GDM (top) and the proposed next generation WSN enabled GDM system*

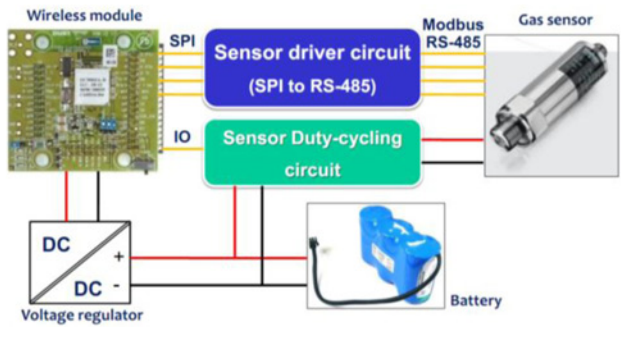

Fig. 2 *Wireless sensor hardware layout*

Table 1 *Gas density monitoring system specification*

Parameter	Value
gas monitoring	range: 0–60 kg/m^3 accuracy: 1% sampling rate: >1 sample/min
temperature	range: –40 to 70°C accuracy: ±2°C
system	battery life: 5–10 years protection: IP65
wireless network	complete data capture signal coverage: 200 m maximum sensors: 256 secure data transfer interface to PC (GUI)

Table 2 *Battery technical characteristics*

Manufacturer	Cell pack solutions UK Ltd
product code	CPS594
based cell	SAFT LS33600
Size	3×D
chemistry	lithium-thionyl chloride, bobbin type
nominal voltage	10.8 V (3 × 3.6 V)
capacity	17 Ah
maximum current	250 mA
useable temperature range	–40 to 70°C
self-discharging rate	<1% after 1 year of storage at +20°C

3 Manufacture of the WSN

Fig. 2 illustrates the hardware layout of the wireless sensor units (motes) within the WSN.

The developed wireless sensor unit is required to qualify for IP65 standard which regulates the enclosure to be proof against 4-µm dust and have good resistance to low-pressure water jets from any angle. Fig. 3 displays the enclosure of the sensor units (motes). The enclosure is made from the common thermoplastic polymer named acrylonitrile butadiene styrene (ABS), allowing the RF wave to transmit through it without any interference. The protection degree of this package is IP66 certified.

Within the following section the WSN experimental analysis consists of: a computer with pre-installed graphical user interface (GUI) application, stargazer application and a terminal program, 1× network manager and 3× sensor units (motes). This is illustrated in Fig. 1.

4 Experimental results and analysis

The first sets of experiments were to verify the wireless communication characteristics of the WSN. Test 1 was conducted in the Heriot–Watt high-voltage (HV) laboratory where a number of metal structures and substation apparatuses are populated, resulting in presence of electromagnetic interference and noise that replicate the substation environment. Fig. 4 provides the overview of WSN deployment within the HV laboratory. In the first experiment, the WSN characteristics that were of interest to verify were: join behaviour of mote, joining time, mesh network formation, path stability, network reliability, received signal strength Indication (RSSI) and latency.

With the join duty cycle set at 25%, three motes took only 1.8 min to finish joining to the network, as shown in Table 3. The manager coordinated the communication with sensor motes, forming the full mesh network in 15 min upon powering up the sensor motes (Fig. 5).

It can be concluded that the HV environment did not have any apparent and serious effect on the system performance because during operation the overall network reliability was very high

Fig. 3 *IP66 packaged wireless sensor unit*

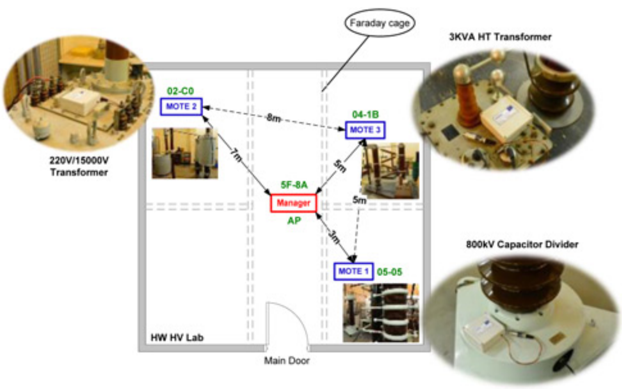

Fig. 4 *Verification of the WSN communications within a HV laboratory*

Table 3 *Time for mote network connections*

Mote (sensor unit)	Time, s
mote 2 (05-05)	9.1
mote 3 (04-1B)	7.4
mote 4 (02-C0)	14.4
	total: 108.6

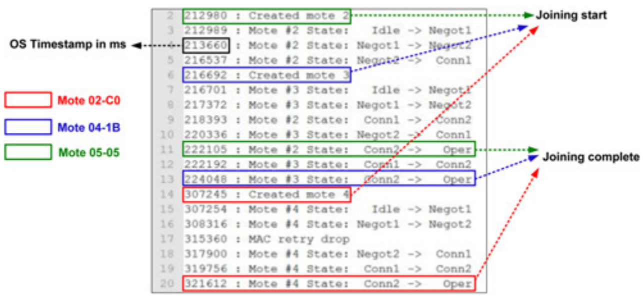

Fig. 5 *Illustration of the joining behaviour of the monitoring motes*

(>95%) while the corresponding value of each mote was 100% stable. The average latency is 72 slots or 522 ms, keeping the transmission of data between manager and motes nearly instant. The RSSI ranged from −76 to −68 dBm, enabling all the motes to have sufficient connectivity in the deployed network.

Test 2 was conducted in the same environment as test 1 and after the network formation finished, one of the parent motes which route the data sent from their children mote to manager was selected to power down, as shown in Fig. 6, causing a path failure. This was to enable the analysis of the transmitted data to see if there was any loss in packet transmission of other motes as well as an observation of the time took for the network to return to a full mesh after a network failure.

Mote 04-1B was powered down to cause two path failures between it and its two children motes 02-C0 and 05-05. Mote 02-C0 now had only one parent (mote 05-05) while mote 05-05 became parentless. Fig. 7 demonstrates the packet received monitoring after the mote powering down happened. Just after about 41 s (1707843–1666677 = 41116 ms), the network has recognised the mote loss and the full-mesh network was re-established 2 s later with two mote 05-05 and 02-C0 as illustrated in Fig. 6.

The results indicated that there was no lost packet detected during the path failures and network recovery. When mote 04-1B was reactivated, it reconnected to the WSN within 5 min.

The third test is related to the power consumption of the WSN. The results showed that the practical power consumption of the entire wireless sensor mote is 1.41 mA h at the sampling rate 0.0167 Hz (one sample per minute). Based on this value, the battery life can be re-calculated as below:

$$\begin{aligned} \text{Battery life} &= 17,000/1.41\ \text{mA h} \simeq 12,057\ \text{h} \\ &\simeq 502\ \text{days} \simeq 1.4\ \text{years} \end{aligned}$$

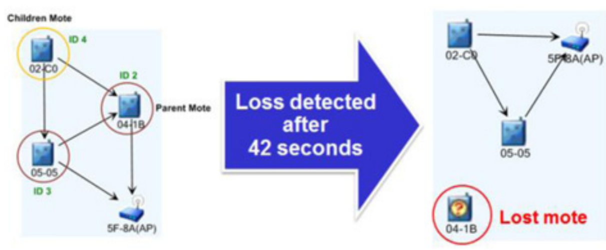

Fig. 6 *Power down of parent mote to induce communication network failure. The WSN detected the failure within 42 s*

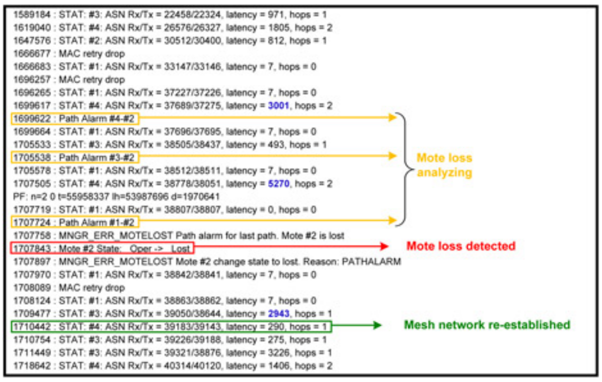

Fig. 7 *Tracing packet received during mote loss event on TeraTerm*

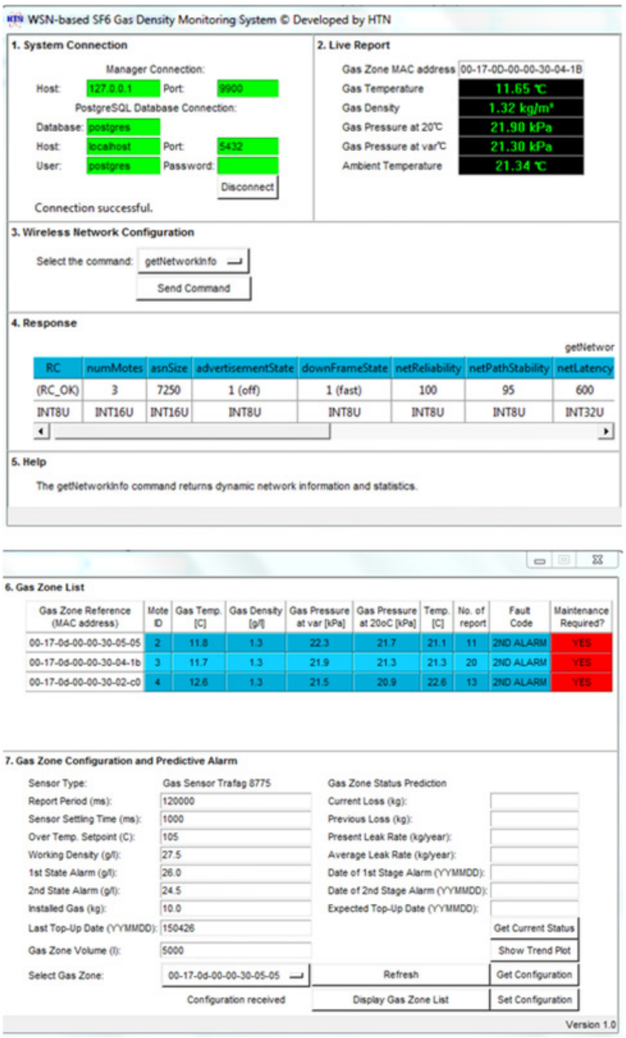

Fig. 8 *Graphical user interface*

There is a significant difference between the practical power consumption and the estimated one. At the same reporting interval, the actual battery life is 1.4 years while based on theoretical calculation the battery can last up to 5 years. This discrepancy is due to several reasons:

(i) Electronic components such as MAX3100, regulator IC LT1761, RS-485 transceiver LTC1480, MOSFETs and transistors are deployed in the circuit but ignored when calculating the current consumption to reduce complexity. Although these components are power efficient (few to hundreds of µA), the cumulative value creates a significant power demand.

(ii) The sensor Trafag 8775 consumes more current than expected. It has been predicted to use only 20 mA when supplied a 10 V input voltage. However, the experimental current consumption was proven to range from 50 to 70 mA which is 3× larger than the estimated current.

The target of increased battery life can still be acquired by slightly reducing the duty cycle or sampling rate of the wireless sensor mote. However, this depends on the particular monitoring application.

The fourth and final test of the WSN was conducted during its deployment within Killingholme 400 kV substation for a short term, 2-day period. The system performed well and transmitted sensor data with 100% reliability.

The GUI of the WSN is shown in Fig. 8.

5 Conclusions

The main deliverable of this project was a WSN demonstrator that outlined solutions to the principle design criteria, such as WSN reliability, communication security, low-power operation, scalable sensor platform, ambient operating conditions and resilient/adaptive configuration of the network topology. The demonstrator sensor network sourced data from SF6 transducers (sensors) to a network manager via an ultra-low power wireless network. The data was displayed via a GUI to enable users to observe the real-time data from sensors that would inform ongoing maintenance. The findings of this research demonstrated the advantageous features of WSN, namely low cost, rapid deployment, adaptive and scalable sensor platform.

In the future, we plan to demonstrate how embedded intelligence, front-end algorithms, can support real-time adaptive measures and centralised operational decision support.

6 Acknowledgments

The authors would like to acknowledge the support of Siemens UK for providing technical support during this project. A special mention to Mr. Huynh who conducted this project during his Smart System Integration MSc working with the Smart Systems Group at Heriot-Watt University.

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